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Super Performance InGaP/GaAs Heterojunction Bipolar Transistor with Hexagonal Emitter*

Liu Honggang, Yuan Zhipeng, He Zhijing and Wu Dexin

(*Microelectronics R&D Center, The Chinese Academy of Sciences, Beijing 100029, China*)

Abstract: Super performance InGaP/GaAs heterojunction bipolar transistors (HBTs) with hexagonal emitter are described. The fabricated HBT shows excellent DC characteristics with low V_{CE} offset voltage (< 0.15V) and low knee voltage (< 0.5V). Over 14V of the collector-base breakdown voltage BV_{CBO} and over 9V of the collector-emitter breakdown voltage BV_{CEO} are obtained. For a self-aligned InGaP/GaAs HBT with 2μm×10μm emitter area, the f_T is extrapolated to 92GHz and f_{max} is extrapolated to 105GHz. These great values are obtained due to the hexagonal emitter and laterally etched undercut (LEU) of collector, indicating the great potential of InGaP/GaAs HBTs for high-speed digital circuit and microwave power applications.

Key words: HBT; InGaP/GaAs; hexagonal emitter

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1 Introduction

AlGaAs/GaAs heterojunction bipolar transistors (HBT) with high efficiency and good linearity are great in wireless communication field. However, InGaP/GaAs HBT has recently received considerable attention because of its potential advantages over AlGaAs/GaAs HBT. The larger valence band discontinuity ($\Delta E_V \approx 0.24eV \sim 0.30eV$)[1] will improve the efficiency of carrier injection; and the smaller conduction band discontinuity ($\Delta E_C \approx 0.03eV$)[2] will eliminate the need for heterojunction grading and ease the materials growth. The lower reactivity of InGaP with oxygen[3], fewer trap-related DX centers with respect to AlGaAs[4], and the higher etching selectivity between InGaP and GaAs are advantages, with which excellent RF performances of InGaP/GaAs HBT have been demonstrated[5,6].

In order to apply InGaP/GaAs HBTs to high-speed digital circuit and microwave power applications, self-alignment techniques and scale reduction for device are required[7]. Several kinds of self-aligned emitter and base HBTs have been reported, including sidewall-separated base electrode structure[8], dummy dielectric emitter[9], T-emitter contact[10], and crystal orientation etching[11]. This last technique is attractive because it requires no special steps of process and has no ion-induced damages. However, the etching of rectangle emitter is anisotropic in nature making the profile of a mesa hill to depend on the wafer crystal orientation, so that over-etching is usually required to ensure electric isolation of emitter and base surrounding it. As a result of thumb, a lager space between emitter

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Liu Honggang male, PhD candidate. His research interests are in HBT devices and RFIC/MMIC.

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and base Ohmic contact will deteriorate RF characteristics of HBT. Using hexagonal emitter, we can precisely control separation of base-emitter metal according to undercut of emitter contact.

In the present work, we propose a novel InGaP/GaAs HBT with hexagonal emitter and laterally etched undercut (LEU) of collector. A 92GHz of current gain cutoff frequency f_T and over 100GHz of a maximum oscillation frequency f_{max} have been achieved from the device with $2\mu m \times 10\mu m$ emitter area.

2 Device fabrication

The InGaP/GaAs epitaxial layers were grown by MOCVD on a semi-insulating GaAs substrate with 4-inch-diameter. The key features of the epitaxial structure were a 50nm InGaP emitter ($n = 3 \times 10^{17} cm^{-3}$), a 60nm C-doped base ($p = 4 \times 10^{19} cm^{-3}$), and a 500nm GaAs collector ($n = 3 \times 10^{16} cm^{-3}$). The base sheet resistance was 240Ω/□. The epitaxial layer structure used for the device fabrication is listed in Table1.

Table 1 HBT epitaxial layer structure

Layer	x	Thickness /nm	Doping /cm^{-3}	Dopant
n^+-$In_xGa_{1-x}As$	0.6	50	$>1\times10^{19}$	Si
n^+-$In_xGa_{1-x}As$	0.6~0	50	$>1\times10^{19}$	Si
n^+-GaAs		120	5×10^{18}	Si
n^--$In_xGa_{1-x}P$	0.5	50	3×10^{17}	Si
p^+-GaAs		60	4×10^{19}	C
n^--GaAs		500	3×10^{16}	Si
n^+-GaAs		500	5×10^{18}	Si
SI GaAs substrate				

A cross-sectional view, presenting a device structure with LEU of collector, is shown in Fig. 1. Self-aligned HBT devices in a standard two-mesa design were fabricated using contact alignment, standard lift-off techniques for metalizations, and all wet chemical etching. A TiPtAu emitter contact was used to mask the emitter etch. The InGaAs/GaAs emitter cap was etched in a citric acid-base solution, which stopped on the InGaP emitter and undercut the emitter contact. The InGaP emitter was then selectively etched using mixed solution of HCl and H_3PO_4. Self-aligned TiPtAu base contacts were then deposited by e-beam evaporation, the width of base Ohmic contact was $1.2\mu m$.

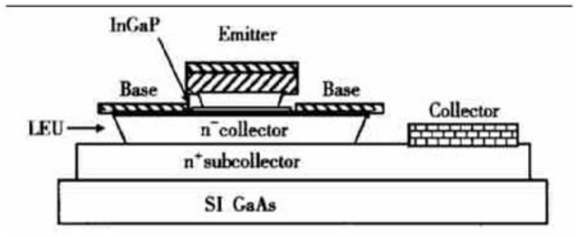

Fig. 1 Cross section of self-aligned InGaP/GaAs HBT with LEU of collector

That wet chemical etching of GaAs is anisotropic in nature makes etching profile depend on crystal orientation. Figure 2 shows how the mesa profiles are etched with respect to different orientation. 〈$\bar{1}$10〉 orientation etching of GaAs usually forms a hillside-slope profile as etched in citric acid-base solution. It is easy to lead to short of emitter-base when depositing self-aligned base contact. Because of hexagonal emitter used, 〈$\bar{1}$10〉 orientation etching of GaAs can be avoided. As a result, the hexagonal emitter ensures that an adequate self-aligned etching can occur on all sides of the emitter electrode, so that base metal can be deposited on all sides of emitter without over-etching required. The effective emitter-to-base spacing can be precisely controlled from $0.2\mu m$ to $0.3\mu m$.

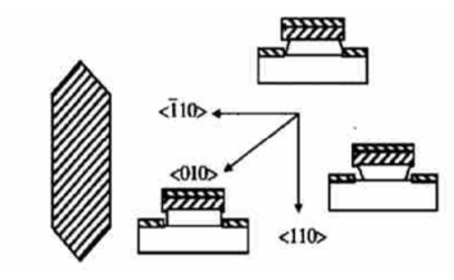

Fig. 2 Crystal orientation etching of GaAs The hexagonal emitter can avoid 〈$\bar{1}$10〉 orientation etching.

Consequently, the base electrode was used to mask the self-aligned base-collector etching. The etchant was the citric acid-base solution. In this step, the structure of LEU for reducing C_{BC} was simultaneously formed. The undercut was about 0.5μm. The AuGeNi/Ag/Au collector was then defined and Ohmic contact was alloyed at 350℃ for 60s in N_2 atmosphere. Finally, the HBT fabrication flow was completed with mesa-isolation, device passivation, polyimide planarization, and TiAu metalization for cascade probing. The optical microscope photograph of InGaP/GaAs HBT is shown in Fig. 3.

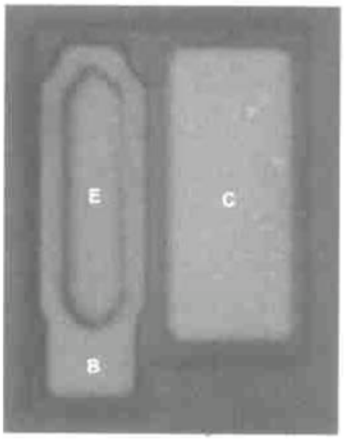

Fig. 3　Optical microscope photograph of InGaP/GaAs HBT with hexagonal emitter　Emitter size is 2μm×10μm; width of base Ohmic contact is 1.2μm; LEU of collector is about 0.5μm

3　Results and discussion

The DC characteristics of InGaP/GaAs HBT were measured by direct probing on the wafer using HP4155 parameter analyzer. Common-emitter current gain h_{FE} dependence on the collector current, for the fabricated HBT with 2μm × 10μm emitter area, is shown in Fig. 4. It can be seen from Fig. 4 that the fabricated HBT delivers a very high current gain over a wider collector current range, peak current gain is over 100, and the threshold current density of Kirk effect is approximately 100kA/cm^2. Especially, HBT devices still exhibit current gain of about 40 at very low collector density (J_C = 1A/cm^2). These results suggest that both generation-recombination current in the intrinsic base region and surface recombination current in the extrinsic base region are negligibly small.

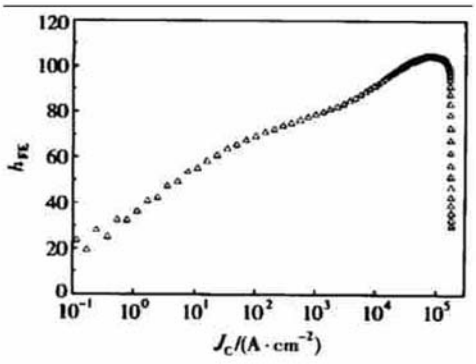

Fig. 4　Current gain as a function of collector current for HBT with 2μm×10μm emitter area

The common-emitter I_C-V_{CE} characteristics for a fabricated HBT with an emitter area of 2μm × 10μm are shown in Fig. 5. The over 80 of DC current gain is obtained. The V_{CE} offset voltage is about 150mV and knee voltage is about 0.5V at collector current of 16mA. The over 14V of collector-base breakdown voltage BV_{CBO} and the over 9V of collector-emitter breakdown voltage BV_{CEO} are obtained. The negative slope in I-V curve is caused by device self-heat effect, which will give rise to the current gain decrease.

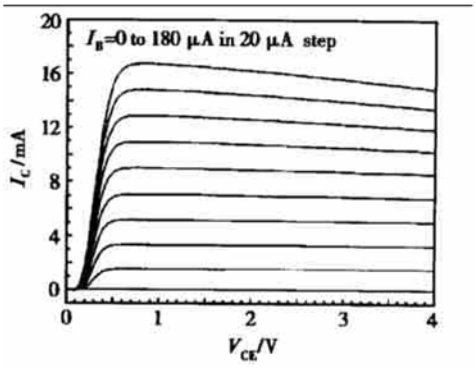

Fig. 5　I_C-V_{CE} characteristics of fabricated HBT with 2μm×10μm emitter area

We investigated the high frequency characteristics of fabricated HBTs using on-wafer probe S-parameters measurements (by HP8510C network analyzer and Cascade microwave probes). The frequency dependence of the small-signal current gain and unilateral gain for a HBT with an emitter area of $2\mu m \times 10\mu m$ is shown in Fig. 6. The measurements were carried out at a collector-emitter bias voltage of 1.5V and a collector current density of $90kA/cm^2$. The f_T and f_{max} as estimated from $-20dB/dec$ extrapolations, were respectively 92GHz and 105GHz. Comparatively, a conventional InGaP/GaAs HBT with rectangle emitter was measured at a same bias, an f_T of 83GHz and an f_{max} of 69GHz were obtained. The higher f_T and f_{max} of the novel HBTs with the hexagonal emitter and LEU of collector were due to the reduction of the base-collector capacitance C_{BC} and base resistance R_B.

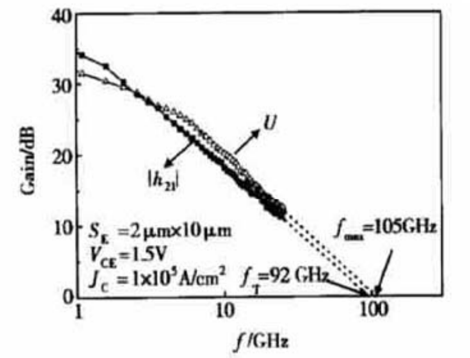

Fig. 6 $|h_{21}|$ and U as a function of frequency for fabricated HBT at $V_{CE}=1.5V$, $J_C=90kA/cm^2$ The dashed lines are extrapolations of $|h_{21}|^2$ and U with a $-20dB/dec$ slope.

The dependence of f_T and f_{max} on the collector current density is shown in Fig. 7. Decrease of the f_T and f_{max} beyond $J_C=90kA/cm^2$ is attributed to

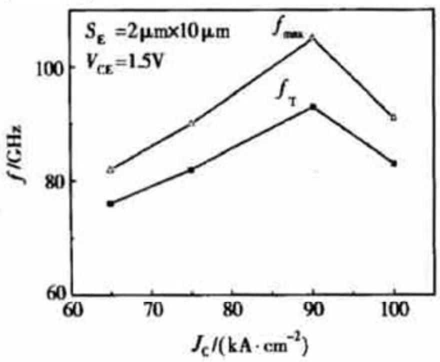

Fig. 7 f_T and f_{max} versus J_C of fabricated HBT with hexagonal emitter at $V_{CE}=1.5V$

the increased collector transit time due to the Kirk effect. The novel InGaP/GaAs HBTs have been successfully applied to 10GHz electro-absorption modulator (EAM) driver in DWDM fiber-optic telecommunication systems.

4 Conclusion

We demonstrated super performance InGaP/GaAs HBT with hexagonal emitter and LEU of collector. The fabricated discrete devices showed excellent DC characteristics with low V_{CE} offset voltage (< 0.15V) and low knee voltage (< 0.5V). The over 14V of collector-base breakdown voltage BV_{CBO} and over 9V of the collector-emitter breakdown voltage BV_{CEO} were obtained. For a self-aligned InGaP/GaAs HBT with $2\mu m \times 10\mu m$ emitter area, the f_T was extrapolated to 92GHz and f_{max} was extrapolated to 105GHz. These results indicated the great potential of InGaP/GaAs HBTs for high-speed digital circuit and microwave power applications.

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高性能六边形发射极 InGaP/GaAs 异质结双极型晶体管*

刘洪刚　袁志鹏　和致经　吴德馨

(中国科学院微电子中心, 北京 100029)

摘要: 六边形发射极的自对准 InGaP/GaAs 异质结具有优异的直流和微波性能. 采用发射极面积为 2μm×10μm 的异质结双极型晶体管, V_{CE}偏移电压小于 150mV, 膝点电压为 0.5V(I_C= 16mA), BV_{CEO}大于 9V, BV_{CBO}大于 14V, 特征频率高达 92GHz, 最高振荡频率达到 105GHz. 这些优异的性能预示着 InGaP/GaAs HBT 在超高速数字电路和微波功率放大领域具有广阔的应用前景.

关键词: 异质结双极型晶体管; InGaP/GaAs; 六边形发射极

EEACC: 2560F; 2550E

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刘洪刚 男, 博士研究生, 从事 HBT 器件及 RFIC/MMIC 研究.

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